NA62

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1 The NA62 experiment

The branching ratios (BRs) for the extremely rare decays $K \to \pi\nu\bar{\nu}$ are among the observables in the quark-flavor sector most sensitive to new physics. Because these decays are strongly suppressed and their BRs are calculated very precisely in the Standard Model (SM), they are excellent probes for new physics at mass scales of hundreds of TeV, surpassing the sensitivity of B-meson decays in many SM extensions. For the $K^+ \to \pi^+\nu\bar{\nu}$ decay, the SM predicts a BR of $(8.4 \pm 1.0) \times 10^{-11}$, making the detection and measurement of this decay extremely challenging. The NA62 experiment [1)] at the CERN SPS took data from 2016 to 2018, collecting 20 candidate $K^+ \to \pi^+\nu\bar{\nu}$ events, demonstrating the validity of the decay-in-flight measurement technique and allowing this BR to be determined to within about 40% [2)] NA62 resumed data taking in 2021 and has been running annually ever since. The analysis of data from the years 2021 and 2022 was completed in 2024, reducing the uncertainty on BR($K^+ \to \pi^+\nu\bar{\nu}$) to 25%, as described below. NA62 will continue running until the start of the LHC Long Shutdown 3 in 2026. By this time, NA62 expects to collect about 60 candidate events for a measurement of BR($K^+ \to \pi^+\nu\bar{\nu}$) to better than 20%.

The NA62 experiment, illustrated in Fig. 1, makes use of a 75 GeV unseparated positive secondary beam. The total beam rate is about 600 MHz, providing nearly 40 MHz of K^+ mesons. The decay volume begins 105 m downstream of the production target. 6 MHz of kaon decays are observed in the 65-m long fiducial vacuum decay region by means of tracking and particle-identification systems. Ring-shaped large-angle photon vetoes (LAVs) are placed at 12 stations along the decay region and provide full coverage for decay photons with 8.5 mrad $< \theta <$ 50 mrad. The last 35 m of the decay region hosts a dipole spectrometer with four straw-tracker stations

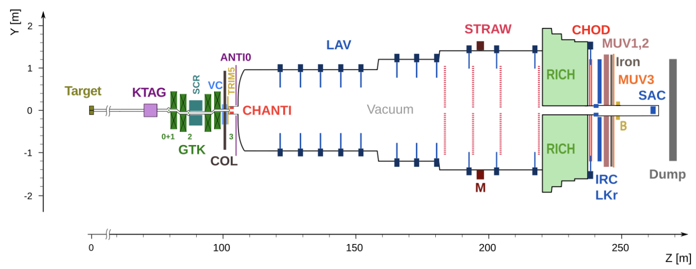

Figure 1: *Schematic view of the NA62 experiment, showing the kaon production target, KTAG Cherenkov K^+ beam tagger, GTK beam tracker, CHANTI collar veto, LAV large-angle photon vetoes, STRAW straw-tube trackers, RICH ring-imaging Cerenkov detector, CHOD hodoscope, MUV1-3 hadron calorimeters and muon vetoes, LKr calorimeter, and IRC and SAC small-angle photon vetoes.*

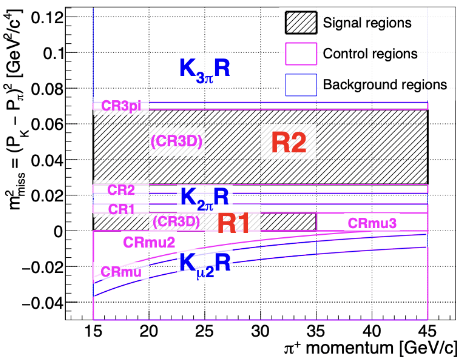

Figure 2: *Definitions of signal and control regions in the* $(p_{\pi^+}, m^2_{\rm miss})$ *plane.*

operated in vacuum. The NA48 liquid-krypton calorimeter (LKr) is used to veto high-energy photons at small angle. Additional detectors further downstream extend the coverage of the photon veto system, including the small-angle calorimeter (SAC), to intercept photons that would exit the experiment through the downstream beam pipe, and the intermediate ring calorimeter (IRC), to provide veto coverage between the LKr and the SAC. The IRC and SAC are collectively referred to as the small-angle vetoes (SAV).

2 New measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio

The 2016–2018 NA62 data sample, leading to the measurement of BR($K^+ \to \pi^+\nu\bar{\nu}$) to 40%, contained about 4×10^{12} K^+ decays in the fiducial volume. In 2021-2022, NA62 collected an additional 3×10^{12} K^+ decays. Improvements to the beam line made during the 2018 run and during LS2, including the addition of new detectors for the rejection of upstream background, together with improvements to the analysis, led to a significant increase in signal acceptance, especially relative to the 2016–2017 data.

The analysis is mainly based on kinematic cuts and particle identification. The invariant $m^2_{\rm miss} = (p_{K^+} - p_{\pi^+})^2$, where p_{K^+} and p_{π^+} are the K^+ and π^+ 4-momenta, is used to discriminate between signal and background. Fig. 2 shows the definition of the signal regions R1 and R2 in the $(p_{\pi^+}, m^2_{\rm miss})$ plane. These regions are selected to avoid the bands of correlation from the abundant two-body decays $K_{\mu 2}$ and $K_{\pi 2}$, as well as the region populated by $K_{\pi 3}$ decays. Regions for the definition of background samples and control regions for validation of background estimates are also defined.

The calorimeters and RICH provide π^+ identification and μ^+ rejection, in order to suppress residual $K_{\mu 2}$ background by a factor of 10^{-7}, while the photon veto system suppresses background from $K_{\pi 2}$ by a factor of 10^{-8}. The remaining background is from decays and interactions of beam particles in the beamline just upstream of the fiducial volume, including in particular events in which a pion from a K^+ decaying while traversing the GTK is detected in the straw chambers and is matched with another beam particle leaving a track in the GTK in accidental time coincidence. These events are suppressed by a multitude of topological and timing cuts.

Fig. 3, left, shows the distribution of the observed events in the $(p_{\pi^+}, m^2_{\rm miss})$ plane after application of all signal selection cuts, including the events in the background, control, and signal regions. At the SM value of the BR, 9.91 ± 0.34 $K^+ \to \pi^+\nu\bar{\nu}$ events are expected; the total number of background events expected is $11.0^{+2.1}_{-1.9}$. A total of 6 events are observed in R1 and 25 events in R2. The $m^2_{\rm miss}$ projection, including the background spectra and SM signal expectation, is shown in Fig. 3, right. The resulting value of the branching ratio is

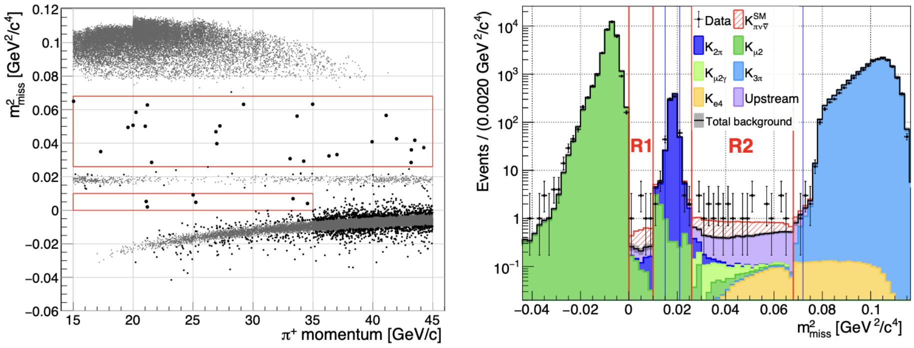

Figure 3: *Left: Distribution of observed events satisfying the signal selection criteria in the $(p_{\pi^+}, m^2_{\text{miss}})$ plane. Events in the background, control, and signal regions are shown by small grey, small black and large black markers, respectively. Right: m^2_{miss} projection including SM signal and background expectations. The total expected background and its uncertainty is shown by the black line and hatched bars, respectively. In the signal region R1, events in the momentum range 35–45 GeV are excluded.*

$$\text{BR}_{2021-2022}(K^+ \to \pi^+ \nu\bar{\nu}) = (16.2^{+4.9}_{-4.3}|_{\text{stat}} \pm 1.4_{\text{syst}}) \times 10^{-11}.$$

In combination with the data from 2016–2018, NA62 obtains

$$\text{BR}_{\text{NA62}}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.0}_{-2.7}|_{\text{stat}} \pm 1.3_{\text{syst}}) \times 10^{-11}.$$

For the full 2016–2022 dataset, with an expectation of 18^{+3}_{-2} background events and 51 signal candidates observed, the p-value of the background-only hypothesis is 2×10^{-7}. Therefore, for the first time, the background-only hypothesis is rejected with significance greater than 5σ, which marks the first observation of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay. These results have recently been published [3]. The $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio measurements and the updated experimental and theoretical status are summarized in Fig. 4.

This result was made possible in part by significant contributions from members of the Frascati team. In addition to having participated in data taking with roles in run coordination and responsibility for maintenance and operation of the photon veto systems, LNF team members made significant direct contributions to the analysis. In particular, the LNF team includes one of the analysis coordinators, a corresponding author of the published result.

3 NA62 data taking in 2024

During 2021–2022 data taking, it was determined that running at 70% of the design value of the primary beam intensity optimizes the sensitivity of the experiment, so from 2023 onward, NA62 took data at this intensity. In 2024, the experiment ran from the start of April through the month of October, for a total of 29 weeks. Short periods of data taking were also dedicated to running in beam-dump mode, for exclusive searches for the production of long-lived, exotic particles, and in low-intensity mode, for studies requiring tight control over experimental systematics, such as first-row CKM unitarity tests. In dump-mode running, a total integrated flux of 2.2×10^{17} protons was dumped on the NA62 collimator, bringing the NA62 total to about 6×10^{17} protons dumped, out of 10^{18} to be collected before LS3. In low-intensity running, a total flux of 2.6×10^{15} protons on target was integrated, corresponding to more than 3×10^9 K^+ decays in the fiducial volume. LNF team members were the main proponents of both the dump-mode and low-intensity data taking

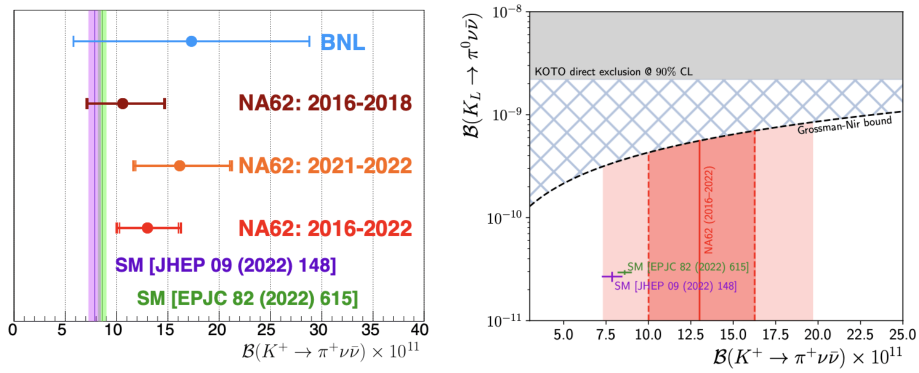

Figure 4: *Left: summary of $K^+ \to \pi^+\nu\overline{\nu}$ branching ratio measurements from the BNL E787 and E949 experiments, and the NA62 experiment using the 2016–2018, 2021–2022 and 2016–2022 data. Statistical and total uncertainties are shown by thinner and thicker vertical bars, respectively. These are compared to the two recent SM predictions. Right: global status of the $K \to \nu\overline{\nu}$ decay modes, showing the most stringent $B(K_L \to \pi^0\nu\overline{\nu})$ upper limit from the KOTO experiment, the Grossman-Nir bound, the two recent SM predictions, and the $B(K^+ \to \pi^+\nu\overline{\nu})$ result from the combined 2016–2022 NA62 dataset (the 1 σ and 2 σ ranges are displayed in darker and lighter shaded areas, respectively).*

campaigns and helped to organize both data-taking periods to ensure the collection of high-quality data. Throughout the run, LNF team members also provided general support to the experiment, with periods of service in the roles of run coordinator and data-quality expert.

4 LNF group activities

4.1 Maintenance and operation of photon veto systems

In 2024, the LNF group prepared the LAV and SAV systems for the restart of NA62 data taking and operated and monitored the performance of the detectors throughout the 29-week running period. In particular, the group made the following contributions:

- Thorough diagnostics and repair of the LAV and SAV detectors and front-end electronics boards in preparation for data taking in 2024.
- Continuous on-call expert support throughout the entire period.
- Improvement and optimization of the simulation and reconstruction code for the LAV and SAV systems.
- Management of data quality, with emphasis on the LAV and SAV detectors.
- Analysis of data acquired in previous years and measurement of system performance.

The LAV system consists of 12 detector stations arranged at intervals of 6 to 10 m along the vacuum tank along its entire length. Each station consists of four or five rings of lead glass blocks, with the blocks staggered in azimuth in successive rings. The total depth of a five-layer station is 27 radiation lengths. This structure guarantees high efficiency, hermeticity, and uniformity of response. The readout chain for the LAV stations consists of two different types of boards, a dedicated front-end board (LAV-FEE) developed for the LAV detector, and a common digital readout board (TEL62) used by many of the NA62 detectors. The LAV detectors and the front-end electronics were designed and constructed at LNF between 2008 and 2014.

The small-angle veto detectors, SAC and IRC, are shashlyk-type electromagnetic calorimeters that provide veto coverage for photons with polar angles down to zero degrees. They are exposed to a very high rate of photons from kaon decays and, for the IRC, muons from pion and kaon decays. The IRC was assembled at LNF in 2014.

4.2 Machine learning for GTK reconstruction

Enhancing the current particle tracking system for the GigaTracker 4-D pixel tracking stations could lead to significant improvements in downstream physics analyses. To explore this possibility, Frascati team members are investigating the application of machine learning (ML) algorithms for particle tracking using Monte Carlo simulations. Specifically, the performance has been evaluated for multi-layer perceptrons, transformer encoders and graph neural networks; these studies have demonstrated that the latter two architectures achieve high efficiency and purity while maintaining a low rate of false positive track candidates. The formulation of the problem accommodates two scenarios: one in which multiple hits from the same particle within a GTK station are clustered, and another in which no clustering technique is applied. Notably, the approach remains robust even when this constraint is removed. Currently, integration of the transformer-based architecture into the NA62 offline framework is in progress, along with the necessary pre- and post-processing steps and a well-defined set of metrics to benchmark its performance against the existing reconstruction method. The model, trained on MC samples, has been applied to a sample of identified $K^+ \to \pi^+\pi^+\pi^-$ events in real data. This allows identification of the "true" data track to be matched, and demonstrates the robustness of the ML method. The effects on the K-π matching performance (in the matching efficiency and in the probability for incorrectly matching with upstream tracks are not the true kaon track) are being evaluated.

4.3 First-row CKM unitarity tests

Precision tests of the first-row unitarity of the Cabibbo–Kobayashi–Maskawa (CKM) matrix currently display two intriguing tensions, both at the $\sim 3\sigma$ level. First, the combination of the determinations of V_{ud} from superallowed β decays with V_{us} from kaon decays suggests a deficit in the unitarity relation. At the same time, a tension of similar significance has emerged between the values of V_{us} obtained with $K_{\mu 2}$ and $K_{\ell 3}$ decays. As one of the only currently running experiments with the ability to measure K^+ decays, NA62 is well positioned to clarify this situation, principally through measurements of the branching ratios of the dominant K^+ decays. In particular, a measurement of the ratio $\mathrm{BR}(K_{\mu 3})/\mathrm{BR}(K_{\mu 2})$ at the level of 0.2% would significantly clarify the experimental situation. With NA62 event rates and acceptances for decays such as $K_{\mu 2}$ and $K_{\mu 3}$, the statistics needed for the measurement of this ratio to better than 0.1% can be collected in a few hours. However, the primary challenge for a measurement at this level of precision is systematic, not statistical. This measurement therefore requires a dedicated data-taking period with the experiment running with a minimum-bias trigger and at $\sim$1% of the nominal primary beam intensity, to eliminate effects from pile-up, which are poorly understood at this level of precision. One week of data taking under these conditions is sufficient to collect more than 3×10^9 K^+ decays in the fiducial volume; in addition, the concentration of the data-taking campaign in a limited period facilitates the control of time-variable conditions.

In 2024, Frascati team members proposed, organized, and helped to carry out a 7-day low-intensity run to collect data for precision tests with abundant K^+ decays, including primarily the measurement of branching ratios for first-row CKM unitarity tests, as well as studies of $K_{\ell 3}$ form factors and other precision observables. The data from this run are currently under analysis, with

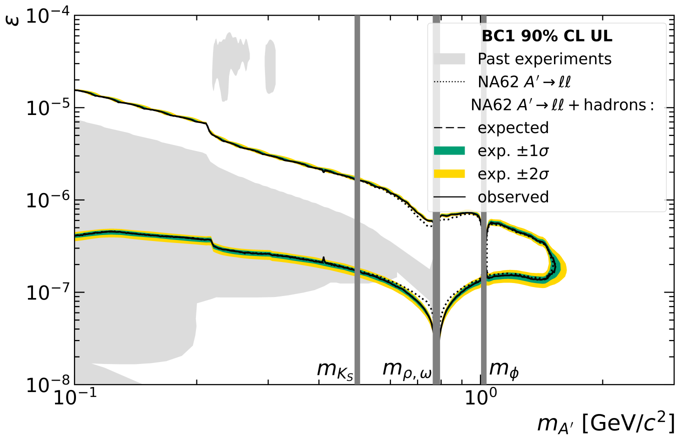

Figure 5: *Search for dark photons leptonic and hadronic decays using NA62 beam dump data corresponding to* 1.5×10^{17} *dumped protons: expected and observed exclusion bounds at 90% confidence level* [5].

the Frascati team coordinating the activities of the working group and leading the analysis of the observable $\mathrm{BR}(K_{\mu3})/\mathrm{BR}(K_{\mu2})$. A second one-week run is planned for 2025, as a check on the final systematics.

4.4 Exotic particle decays

The responsibility of the NA62 working group "Exotic searches" is shared by one of the LNF researchers in NA62. The activity is focused on the search for visible decays of feebly-interacting particles (FIPs). These are produced after interactions of the beam protons with the material of a movable collimator (TAX), in dedicated "beam-dump" runs. Data has been collected in beam-dump mode in the years 2021, 2022, and 2024. After the search for di-muon decays of exotic particles, published in 2022, the sensitivity has been widened. In 2024, the result from the search for decays to e^+e^- and the related combination with the di-muon result has been published [4]. Moreover, a preliminary result for the search for hadronic FIP decays (with/without accompanying photons/π^0s/ηs in the final state) has been presented [5]. These results are based on the 2021 data set, corresponding to 1.5×10^{17} protons dumped on the tax (POT).

All of the above searches have been consistent with the absence of any FIP-induced signal, allowing exclusion of new regions of the parameter space (FIP mass, coupling to SM particles) for dark photons, dark scalars and axion-like particles. For example, the impact of NA62 searches for the dark photon case is shown in Fig. 5. The impact for axion-like particle models is comparable to that of the dark photon. For dark scalars, lifetime effects limit the sensitivity to below 500 MeV, still improving over the past experiments, as shown in Fig. 6.

Notwithstanding their null results, the searches mentioned are background free and therefore the lower bounds of the exclusion limits depend only on the collected number of proton interactions. A new data taking in beam dump mode has been requested and approved for 2025. The goal is set to reach an integrated POT of 10^{18}. This will allow extending the physics case to include semi-leptonic decays, typical signatures of the heavy-neutral leptons (HNL). A number of researches within the "Exotic searches" group performed a phenomenology study with the goal of evaluating the impact of the present theoretical uncertainties to the sensitivity of HNL searches [6]. The conclusion is that the collection of 10^{18} POT at NA62 will allow exploring new region of the

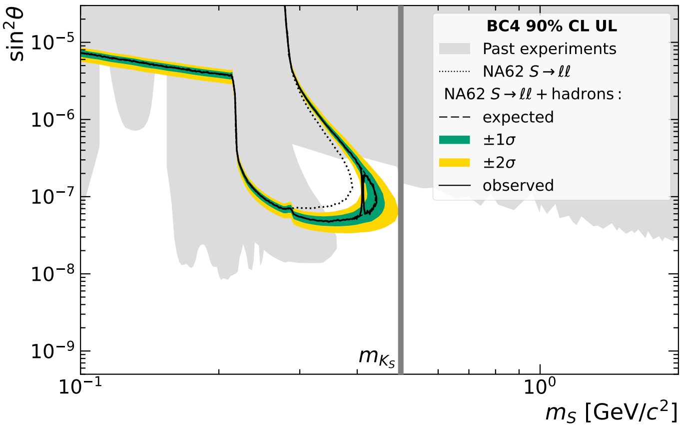

Figure 6: *Search for dark scalars leptonic and hadronic decays using NA62 beam dump data corresponding to* 1.5×10^{17} *dumped protons: expected and observed exclusion bounds at 90% confidence level* [5].

parameter space in a number of HNL flavour scenarios.

4.5 Future kaon experiments

Since the start of NA62 data taking, the Frascati group has had a leading role in planning the future of the rare-kaon decay program at CERN. Before 2020, this effort focused mainly on conceptual studies for KLEVER, an experiment to measure BR($K_L \to \pi^0\nu\bar{\nu}$). In 2020, NA62 articulated a long-term plan for a program at a high-intensity kaon facility, consisting of the following phases:

1. A high-statistics K^+ experiment to measure BR($K^+ \to \pi^+\nu\bar{\nu}$) to 5%.
2. A transitional experiment making use of the K_L beam for KLEVER and the downstream detector with tracking and PID from the K^+ experiment to investigate other rare K_L, decays such as $K_L \to \pi^0\ell^+\ell^-$.
3. A high-statistics K_L, experiment to measure BR($K_L \to \pi^0\nu\bar{\nu}$) to 20% (KLEVER).
4. Additional running in beam-dump mode to attain the highest possible precision in searches for exotic physics, as discussed in the previous section, to the maximum extent compatible with the rare kaon decay program.

The program outlined above was presented to the CERN SPSC as HIKE—High Intensity Kaon Experiments at the CERN SPS—in a Letter of Intent in November 2022 [7]. The formal proposal for HIKE [8] was submitted in October 2023. Frascati team members had leading roles in the preparation of these proposals. In particular, the calorimeter and photon veto systems, originally conceptually designed for KLEVER, were adopted as baseline solutions for HIKE, and Frascati became the locus for R&D work on two important detector systems for future experiments—the main electromagnetic calorimeter, to replace the NA48 LKr calorimeter, and the KLEVER small-angle calorimeter (SAC). R&D on both systems has been in progress at Frascati for the past few years, in part within the framework of the AIDAinnova research infrastructure.

In March 2024, the CERN management elected to locate the SHiP experiment for hidden-particle searches in the ECN3 cavern, effectively setting a deadline for the termination of the study

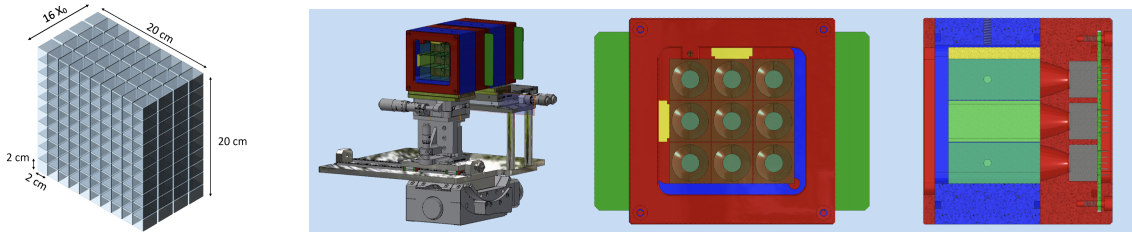

Figure 7: Left: Dimensional sketch of a SAC based on dense, high-Z crystals with both transverse and longitudinal segmentation. Right: Mechanical designs for HIKE SAC prototype. From left to right: complete assembly, including mechanics for relative positioning and angular rotation between layers; front view, sectional side view showing Winston cones and PMTs.

of kaon physics at CERN with the conclusion of NA62 data taking at the start of LS3, in 2026. The detector R&D program currently in progress at Frascati is currently being wound down, with support from the NA62 Collaboration and CSN1 to complete the current round of prototypes, so that the experience gained in preparation for HIKE may benefit future experiments.

4.5.1 HIKE Small-Angle Calorimeter

An ideal solution for a small-angle calorimeter for HIKE, capable of sustaining the expected rates and relatively transparent to beam neutrons during the K_L, phases, is a highly granular, longitudinally segmented, fast, crystal calorimeter, as conceptually illustrated in Fig. 7, left. CRILIN, an electromagnetic calorimeter under development for the International Muon Collider Collaboration, is an independently proposed concept for a crystal calorimeter of similar design with SiPM readout and performance requirements comparable to those for the HIKE SAC. Much development work for the HIKE SAC has been carried out at Frascati in collaboration with the CRILIN group. In 2024, with the continued collaboration of the CRILIN group, a prototype specifically designed to meet the performance requirements for the HIKE SAC was conceptually designed. With respect to previous CRILIN prototypes, the HIKE prototype uses readout with fast PMTs and ultrafast lead tungstate (PWO-UF) crystals with larger cross section (18×18 mm^2). The choice of PWO-UF is necessary in order to withstand the radiation exposure from in-beam operation, as is readout with PMTs [9]. The required time resolution can be obtained with compact metal-package PMTs such as Hamamatsu's R9880 or R14755 models. These tubes, measuring just 16 mm in diameter by 12 mm in thickness, can be soldered directly onto a readout backplane, like the SiPMs used in the CRILIN design. Because of the small photocathode area (8 mm diameter), the calorimeter module incorporates Winston cones to improve light collection. A prototype with 2 layers of 3×3 crystals, as illustrated in Fig. 7, right, is under construction and will be tested in late August 2025 at the CERN PS. The mounting mechanics includes linear and rotational stages to allow precision angular alignment between the layers, allowing the 9 crystals in each layer to have their crystal axes aligned and the crystals to be glued together as in the OREO prototypes [10]. This will allow operation as a fully-aligned crystal calorimeter prototype in collaboration with the OREO group once the prototype has been validated with respect to its performance baseline. Development of the HIKE SAC is synergetic with DRD6, in which both CRILIN and OREO are represented. The HIKE SAC design is being evaluated for use in the KOTO II at J-PARC, a new experiment proposed to carry out a next-generation measurement of BR($K_L \to \pi^0 \nu \bar{\nu}$) [11]. Because the photons to be vetoed at KOTO II have much lower energies than in HIKE (single GeV instead of tens of GeV), the prototype has been designed to be reloaded with slower but brighter, radiation hard crystals such as LYSO for future KOTO II validation studies.

Figure 8: Prototype shashlyk module for the HIKE Main Electromagnetic Calorimeter during beam tests at the CERN PS in September 2024.

4.5.2 HIKE Main Electromagnetic Calorimeter

Although the efficiency and energy resolution of the liquid-krypton calorimeter (LKr) used in NA62 appear to be satisfactory for all phases of HIKE, its time resolution is a significant issue. For the K_L phases, and for $K_L \to \pi^0 \nu\bar{\nu}$ in particular, the calorimeter provides the measurement of the event time, and must have a time resolution of 100 ps or better for the reconstruction of π^0s with energies of a few GeV. Additionally, the size of the LKr inner bore would limit the beam solid angle and hence the kaon flux during the K_L phases. The HIKE proposal called for replacement of the LKr with a shashlyk calorimeter patterned on the PANDA FS calorimeter, in turn based on the calorimeter designed for the KOPIO experiment [12]. This design featured modules 110×110 mm^2 in cross section made of alternating layers of 0.275 mm lead absorber and 1.5 mm injection-molded polystyrene scintillator. KOPIO was able to obtain an energy and time resolution of 3.3% and 73 ps at 1 GeV in small prototypes with this design, suggesting that it is capable of providing the same energy resolution as the LKr while meeting the time resolution requirements for HIKE.

In 2024, together with HIKE collaborators from INFN Napoli, Frascati team members tested a full-size prototype shashlyk module for HIKE based on the KOPIO design (Fig. 8). The module, assembled at DETEC (Kharkiv, Ukraine), consists of 9 40×40 mm^2 cells, each with 500 shashlyk layers of 0.3 mm lead and 1.6 mm of injection molded polystyrene scintillator with white TiO_2 paint, for a total depth of 1 m ($27X_0$). Each cell is read out with 16 BCF-92XL 1.2 mm WLS fibers, mirrored at the far end. Two types of photodetectors were tested: silicon photomultipliers (Hamamatsu S13360-6025CS, 25 μm pixel size) and photomultiplier tubes (Hamamtsu R7600U-300, with extended green bialkali photocathodes). The module was tested with both readout schemes during a 7-day run with minimum-ionizing particles and 1–6 GeV electrons in the T9 beamline at the CERN SPS in September 2024. The time resolution, energy linearity, and energy resolution were studied. Relative to the original KOPIO module, there is some degradation of the time and energy resolution, possibly due to the much larger depth of the shashlyk stack in the HIKE prototype; this was to some extent expected. The data are currently under analysis, including detailed comparisons with simulation, and additional tests with faster fibers, faster PMTs, and different readout schemes (including dual side readout) are planned for the future. The next test is scheduled for September 2025.

4.5.3 Novel scintillators

Although current information suggests that optimized formulations of conventional polystyrene scintillator are sufficiently luminous, fast, and radiation resistant for use in a shashlyk calorimeter such as for HIKE, in synergy with the AIDAinnova project NanoCal, Frascati team members are evaluating the advantages that can be obtained with less conventional choices for the light emitter.

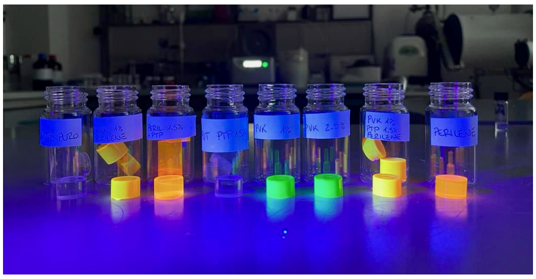

Figure 9: Conventional scintillator, nanocomposite scintillator, and control samples for light yield measurements at the Frascati BTF and CERN PS, seen under ultraviolet light.

In 2022 and 2023, we participated in a head-to-head experimental comparison of small shashlyk prototypes made from conventional scintillator, specifically, the extrusion-moulded polystyrene scintillator formulated at IHEP Protvino for KOPIO, with 1.5% PTP and 0.04% POPOP, and a nanocomposite scintillator consisting of 0.2% cesium lead bromide (CsPbBr3) nanocrystals in PMMA [13]. The latter, which emits in the green at 520 nm, is expected to be a very fast and bright alternative to conventional scintillators; its comparatively long wavelength emission and use of PMMA as a matrix material is expected to confer good radiation hardness. However, the results of these tests indicated no significant improvements in the light yields. From mid 2023 onward, therefore, the emphasis of the project was on the identification of a more suitable composition for the nanocomposite scintillator. Two possible hypotheses to explain the low light yield were identified: (1) excess self-absorption by the nanoparticles, and (2) inefficient excitation of the nanoparticles, whether because of their low concentration or because of the lack of an efficient channel for the transfer of energy to the nanoparticles from the polyacrylate matrix. To mitigate the self-absorption of the scintillation light by the nanoparticles, we have experimented with nanocomposite formulations including additional wavelength-shifting dyes. To facilitate energy transfer from the matrix to the nanocrystals we have focused on the development of nanocomposites with an aromatic matrix material. For these studies, we use smaller samples of scintillator, typically of about 1 cm^3 in volume, with direct light readout. Many samples prepared by our collaborators at the University of Milano Bicocca were tested at the CERN PS with mips and at the Frascati BTF with 450-MeV electrons (which have mip-like energy deposit for small samples) in late 2023 and early 2024. Samples of both conventional molecular (including some commercial standards) and nanocomposite scintillator were tested for comparison, together with a number of control samples consisting of only the non-scintillating materials (the matrix materials, in some cases together with the WLS dyes used in some of the nanocomposites). Several of these samples are seen in Fig. 9. The data from these test beam exposures are underway; in addition, together with our collaborators at Milano Bicocca and CERN, we are performing detailed spectroscopic, photoluminescence, and radioluminescence studies, as well as measurements with radioactive sources. Some preliminary conclusions have been presented at conferences [14, 15]. At the moment, our results suggest that the use of perovskite quantum dots to make an NC scintillator for high-energy physics is not straightforward. The realization of the promise of these materials for the creation of very fast, bright, and radiation-tolerant scintillators for high-energy physics will require efforts to increase the light output, Once a promising candidate has been identified, we are ready to proceed with the construction of new prototypes.

As a side note, various of our control samples containing only conventional primary scintillating molecules and wavelength shifting dyes have shown unexpectedly large light yields and fast emission times. This has led to a side program for the investigation of promising candidates for new, bright, fast organic scintillators with comparatively long emission wavelengths (i.e., in the green-to-orange band), which might be expected to confer additional radiation resistance.

Conference talks by Frascati team members

S. Martellotti

- "Recent results in kaon physics: NA62", 22nd Conference on Flavor Physics and CP Violation (FPCP 2024), Bangkok, Thailand, March 2024

M. Moulson

- "The search for new physics with kaon decays at the CERN SPS", The Flavour Path to New Physics, University of Zurich, June 2024
- "Development of nanocomposite scintillators for high-energy physics", Kaons@J-PARC 2024, J-PARC, Tokai, Japan, July 2024

L. Plini

- "Algoritmi di machine learning per il tracciamento di particelle all'esperimento NA62", Incontri di Fisica delle Alte Energie (IFAE 2024), Firenze, April 2024
- "Deep Learning Techniques for Particle Tracking in NA62", Workshop Italiano sulla Fisica ad Alta Intensità (WIFAI 2024), Bologna, November 2024

M. Soldani

- "Physics Beyond the Standard Model with the NA62 experiment at CERN", 14th Excited QCD Workshop (EQCD 2024), Benasque, Spain, January 2024
- "Innovative nanocrystal-based scintillators for next-generation sampling calorimeters", 20th International Conference on Calorimetry in Particle Physics (CALOR 2024), Tsukuba, Japan, May 2024
- "R&D on a high-performance electromagnetic calorimeter based on oriented crystalline scintillators", 20th International Conference on Calorimetry in Particle Physics (CALOR 2024), Tsukuba, Japan, May 2024
- "Concepts of a crystalline small angle calorimeter", Kaons@J-PARC 2024, J-PARC, Tokai, Japan, July 2024

T. Spadaro

- "Searches for dark messengers at NA62: a focus on hadronic final states", Vulcano Workshop 2024: Frontier Objects in Astrophysics and Particle Physics, Ischia, May 2024

J. Swallow

- "Latest results on rare kaon decays", Vulcano Workshop 2024: Frontier Objects in Astrophysics and Particle Physics, Ischia, May 2024
- "New measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay by the NA62 Experiment", seminar:
  - CERN EP Seminar, 24 September 2024
  - LNF General Seminar, Frascati, 8 October 2024

– HEP Seminar, Imperial College London, 9 October 2024
– Aperitivo Scientifico, INFN Bologna, 5 November 2024
– Experimental Particle Physics Seminar, University of Edinburgh, 8 November 2024
– Cavendish High Energy Physics Seminar, University of Cambridge, 19 November 2024
– Particle Physics Seminar, University of Birmingham, 20 November 2024
– Elementary Particle Physics Seminar, University of Warwick, 21s November 2024
– Experimental Particle Physics Seminar, Lancaster University, 22 November 2024
– High Energy Physics Laboratory (LPHE) Seminar, École Polytechnique Fédérale de Lausanne (EPFL), 16 December 2024

G. Tinti

- "First NA62 search for long-lived new physics particle hadronic decays", 22nd Conference on Flavor Physics and CP Violation (FPCP 2024), Bangkok, Thailand, March 2024
- "Status and prospects of rare decay searches at NA62", Workshop Italiano sulla Fisica ad Alta Intensità (WIFAI 2024), Bologna, November 2024
- "New measurement of the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio", Seminar at the Paul Scherrer Institut, Villigen, Switzerland, 13 December 2024

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